Reduction of impact ionisation in GaAs-based planar Gunn diodes by anode contact design

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Abstract.
Impact ionisation in GaAs-based planar Gunn diodes is studied through electroluminescence analysis with the aim of reducing its magnitude by means of contact design and shaping and thus enhance device performance and reliability. Designs in which the diode ohmic anode has an overhanging Schottky extension (composite anode contact) are shown to result in a significantly reduced amount of impact ionisation compared to a simple ohmic contact design. The electroluminescence results are consistent with Monte Carlo simulations which show a reduced impact ionisation in composite anode contact devices due to a reduced electron density beneath the anode Schottky extension that, on the one hand, weakens the Gunn domain electric field and softens its variations near the anode edge, and, on the other hand, reduces the number of electrons capable of generating holes by impact ionisation. A comparison between standard and composite anode contact approaches in terms of RF operation of the devices is made showing oscillations up to 109 GHz with an output power of -5 dBm in devices featuring the composite anode contact and no oscillations from all-ohmic contact devices. The findings reported in this work may be useful not only for the design and fabrication of planar Gunn diodes, but also for other devices such as HEMTs where impact ionisation can result in reliability limitations.

1. Introduction

There is presently great interest in the development of THz sources capable of generating high output powers while keeping the fabrication costs, device sizes and power consumptions to a minimum [1,2,3,4]. Gunn diodes can generate continuous wave signal with low phase noise in the GHz range, with output powers up to 100 mW [5,6,7]. Thus, they are good candidates for mm-wave and THz emission, provided their operation frequency can be extended into the THz regime. The frequency of operation of these devices is determined mainly by the transit time from the cathode to the anode of the spatial charge Gunn domains. Thus, reducing the distance these domains have to travel would result in an increase of the operating frequency. However, Joule heating can become a key limiting issue for the performance of the most common vertical configuration Gunn diodes when the electron density in the channel exceeds 10^{16} cm^{-3}. This electron density limits the active region size to around 1 μm, below which Gunn domains will not have room to form [8]. Thus the operating frequency in the fundamental mode of operation of the common vertical configuration Gunn diodes is typically limited to around 90 GHz in the GaAs material system and 400 GHz in materials based on InP [5].

A planar, high electron-mobility transistor (HEMT)-like structure has been proposed as an alternative to the vertical configuration [9,10,11,12,13]. This planar design opens the possibility of an easier integration of the Gunn diodes in monolithic microwave integrated circuits, in a similar way as reported in Ref. 14. In addition, these planar structures can maintain very high electron densities in the undoped GaAs channel with a reduced scattering of carriers by impurities, which would result in a reduction of the Joule heating. Indeed, it will be possible for cooling devices to be placed closer to the source of heat than in vertical devices, allowing for a more efficient extraction of the heat.

The increased electron densities in the channel permit also the formation of narrower domains, which would in turn allow for shorter device lengths, on the order of several hundred nanometer, allowing thus to extend the operating frequency to the 0.1-1 THz range in the fundamental mode [9, 12]. Previous simulations on InGaAs/InAlAs planar devices have shown the possibility of obtaining Gunn-like oscillations over 1 THz [15]. Moreover, simulations on planar devices similar to those shown in this work predict oscillations at ~150 GHz for 1 μm device length devices [12]. Thus, it is expected that, by reducing the device length below 1 μm, the operating frequency would be well into the hundreds of GHz range. Indeed, it has been previously shown experimentally that devices smaller than 1 μm function as Gunn devices [16].

Furthermore, in the planar configuration, the device active length is defined during the fabrication by choosing the spacing of the top cathode and anode metallic contacts, opening the possibility of fabricating devices operating at different frequencies on a single wafer. Gunn oscillations at frequencies as high as 158 GHz in the fundamental mode of operation have already been demonstrated from 1.3 μm-long GaAs-based planar Gunn diodes [10]. However, the voltages at which these planar devices operate are close to the breakdown voltage, and this can pose reliability issues, reducing the device lifetime.

This planar Gunn diodes reliability issue may be mitigated by the use of so-called composite anode contacts, which consist of an ohmic contact with an overhanging Schottky extension several hundred nanometres in length [17, 18]. Earlier Monte Carlo simulations have shown that the dissipated power at the anode edge of planar Gunn diodes employing this composite anode contact approach should be reduced by a factor of two when compared to devices with two ohmic terminals [18]. Moreover, it has been demonstrated experimentally that this composite anode contact approach increases the breakdown voltage of the planar Gunn diodes by ~1 V, thus shifting it farther away from the typical operating voltage of the devices [18].

It has previously been suggested that in devices featuring composite anode contacts, the most energetic electrons in the travelling Gunn domains may be able to exit the device over the Schottky barrier, whereas the less energetic electrons will continue their path until the edge of the anode ohmic contact. Thus, the energy of the domain field would be spread over a larger volume, thereby reducing the local electric field and the risk of breakdown of the devices. However, there is still no experimental evidence to prove this hypothesis [18]. If the peak electric field inside the channel is reduced in devices with composite anode contacts, the impact ionisation rate, i.e. the rate of electron-hole pair generation by hot electrons, should decrease. Therefore, in this work, the role of the composite anode contact approach on impact ionisation in the device channel is investigated with the aim of shedding light into the working principle of this alternative contact design, and also because impact ionisation is known to perturb the Gunn domains [19, 20], and therefore, its reduction would have further benefits for device performance and reliability. This goal is achieved by comparing impact ionisation-related electroluminescence (EL) from all-ohmic and composite anode contact devices. Monte Carlo simulations of the appearance of impact ionisation events in devices employing both contact strategies were performed to correlate to the experimental data. The here discussed recipes for contact design and shaping of GaAs-based planar Gunn diodes, may also be applicable for any other type of device in which impact ionisation may be a reliability challenge. For example, impact ionisation has been reported in a significant variety of GaAs and InP-based MESFETs and HEMTs [21,22,23,24] and also in GaN-based devices [25].

2. Methodology

2.1 Device structure

The devices used in this work were grown by molecular beam epitaxy on GaAs (100) semi-insulating substrates. The active region structure consists of a 50 nm-thick non-intentionally doped GaAs channel surrounded by two 20 nm-thick $Al_{0.2}Ga_{0.8}As$ layers (Figure 1). Each of these barrier layers is double δ-doped with Si at a density of 8×10^{11} cm^{-2}. The resulting electron density in the channel layer is estimated to be ~10^{17} cm^{-3}. This heterostructure is overgrown using 15 nm of highly doped n-GaAs on top of which multiple GaAs/InGaAs layers are grown to aid the formation of ohmic contacts. The distance between anode and cathode contacts defines the device active length, L_{ac}, which is in the 1-1.5 µm range in this work. The devices have standard ground-signal-ground coplanar contacts to allow for DC and RF on-wafer measurements. More details on the growth and processing of the devices can be found elsewhere [10].

Two different approaches for the design and fabrication of the metallic contacts are employed in this work. First, a series of devices in which both cathode and anode contacts consist of an ohmic metallisation made by the deposition of 20 nm Pd, 50 nm Ge, 10 nm Au, 50 nm Pd and 150 nm Au (see the schematic diagram of Figure 1(b)) which is subsequently annealed at 400 ºC for 60 s. Second, a series of devices in which the cathode contact is ohmic, as in the previous case, whereas the anode features a so-called composite anode contact. This composite anode contact consists of an ohmic contact, similar to that on the cathode side, with a non-annealed Schottky extension consisting of 20 nm Ti/150 nm Au overhanging the ohmic contact towards the anode side. The length of this extension in this work is 300 nm, in order to reach a compromise between low contact resistance and high breakdown voltage [18]. A schematic diagram of the composite anode contact approach is shown in Figure 1(c).

2.2 Experimental methods

The planar Gunn diodes were tested on-wafer at a fixed heat sink temperature of 25 ºC and were DC biased. Current was monitored to ensure no significant degradation occurred during the measurements. Spectrally resolved EL measurements from the devices were recorded using a ×50 microscope lens with a numerical aperture of 0.50 to collect the emitted light which was afterwards dispersed by a diffraction grating and focused on to a Peltier cooled CCD camera. A Renishaw InVia system was used for those measurements. The spectra thus collected were corrected for the spectral response of the experimental setup. EL images of the devices under DC bias were taken through the same microscope lens using an astronomy-grade near-infrared-sensitive CCD camera. Finally, the RF measurements were performed by means of a W-band mixer and a spectrum analyser.

2.3 Monte Carlo simulations

The Monte Carlo simulations of the impact ionisation in the devices were made using a Keldysh model taking bulk impact ionisation rates for the materials that form the device structure. More details on the model can be found in Ref. 26. The structure employed in the simulations was identical to that of Figure 1(a) with the exception that the GaAs/InGaAs contact layers were not included, since they are large and complex to simulate and do not affect the device behaviour significantly. The two contact approaches were implemented as follows. First, all-ohmic devices were simulated assuming a high density of charge beneath both anode and cathode contacts to take into account annealing in a similar way as has been previously reported in Ref. 12 with the difference that, in this work, the high charge density region only extended to the upper barrier of the channel. The differential resistance of these contacts was assumed to be negligible. Second, in the composite anode contact devices, the cathode ohmic contact was constructed in the same way as described in the previous case. The composite anode, on the other hand, was modelled taking the ohmic part of the contact as explained above, and adding the 300 nm-long Schottky extension, with no high electron density underneath it. The differential resistance of this extension was considered negligible for forward bias above threshold. An offset potential between the Schottky contact and the semiconductor of 0.7 V (i.e. roughly half of the semiconductor band gap energy, as often used in Monte Carlo simulations [27]) was assumed in order to account for the Schottky barrier, i.e. the Schottky contact potential is 0.7 V lower than the ohmic contact potential. In order to compare the composite anode contact to the all-ohmic device, the *effective* potential difference (that is, after accounting for any Schottky barrier effects) between the Schottky anode contact and the ohmic cathode was taken as the same as that between the anode and cathode in the all-ohmic devices.

3. Results and discussion

3.1 Electroluminescence from the planar Gunn diode channel

Figure 2 shows the DC *I-V* characteristics of representative planar Gunn diodes featuring both the all-ohmic and the composite anode contact approaches. It is observed that the *I-V* curves flatten for voltages above a value of around ~3 V in both cases. This behaviour is normally attributed to the occurrence of a significant intervalley scattering in the device channel [6, 7, 9]. It is also observed that the current is somewhat higher (~15-25%) in the device with all-ohmic contacts, in both the linear and the saturation regimes. The difference in the linear regime is due to the fact that, in the composite anode contact devices, because of the 300 nm-long Schottky extension in the anode, the distance between the cathode and anode ohmic contact edges is ~20% longer (Figures 1(b) and 1(c)), i.e. the channel resistance is higher. The higher saturation current in the all-ohmic case could be explained in part by the contribution to the current of a higher quantity of holes, which would be generated by a larger impact ionisation in this case. However, it is not possible to draw a clear conclusion in this regard since the saturation current depends on a variety of factors.

At bias voltages in the saturation region of the *I-V* curves, EL starts to be observed from several regions of the device channel, its intensity increasing with applied bias. A representative EL spectrum from an all-ohmic device is shown in Figure 3. It can readily be observed that the EL has a peak near the band gap energy of GaAs of 1.42 eV. The emitted light originates from the recombination between electrons and holes in the GaAs channel, the latter being generated by impact ionisation. This finding is in accordance with what has been reported from a number of structures and devices, such as n-doped GaAs, GaAs p-n junctions [28,29] and a variety of GaAs-based heterostructure HEMTs [21,22,23,24]. Impact ionisation is caused by electrons that acquire enough energy to generate electron-hole pairs due to the strong electric field inside the space charge Gunn domain [22,28,29].

The electron temperature in the Gunn diodes can be estimated from an EL spectrum, as the shape of the high energy tail of the EL spectra reproduces the carrier distribution in the GaAs channel [21,22,28]. Assuming a Maxwellian electron distribution proportional to $\exp(-E/kT_e)$, where E is the photon energy, T_e the electron temperature and k is the Boltzmann's constant, the value of T_e can be extracted from the slope of a linear fit to the high energy tail of the logarithmically-plotted EL spectra (Figure 3). For the shown case of an all-ohmic device, and in the voltage range considered here, the electron temperature increased with applied bias, and was typically up to 1200 K for the voltage range studied. These values of the electron temperature are consistent with what has been previously published by Balkan *et al.* from n-doped GaAs slabs [28].

Images of the EL from the device channel were taken as a function of bias from 0 V to near breakdown. Figure 4 shows representative EL patterns for both all-ohmic (Figure 4(a)) and composite anode contact (Figure 4(b)) devices at 5 V DC bias voltage. It was observed that, in planar Gunn diodes with all-ohmic contacts, light emission takes place more or less over whole channel width, although the EL intensity was often unevenly distributed along the contacts. Closer inspection reveals that EL intensity decreases from the anode to the cathode contact. In contrast to the all ohmic devices, in the composite anode contact devices, EL was typically concentrated on single isolated spots close to the edges of the channel under the same bias conditions, as illustrated in Figure 4(b). This behaviour was observed in the majority of the devices examined. Only when the voltage was increased further (i.e. ~40-50%, higher than EL onset bias for the all-ohmic counterparts) EL was also observed from the centre regions of the device in some of the composite anode contact planar Gunn diodes, although, in most cases, no light emission from the centre of the channel was detected at all in the voltage ranges considered. These results indicate that the use of the composite anode contacts hinders the appearance of EL related to impact ionisation, except on those regions of the channel where border effects play a role (i.e. the device edges). The observed variations in EL intensity along the contacts in the all-ohmic device could also be in part related to limitations in contact fabrication and effects of variations on the intermixing length of the metals after contact annealing.

Figure 5 shows the EL intensity, integrated over the whole channel area of the devices, obtained from the EL images, as a function of applied bias for the all-ohmic and composite anode contact devices. It is readily observed that the EL integrated intensity was significantly higher for the case of the device with all-ohmic contacts at the same bias conditions. It is worth to keep in mind that the EL integrated intensity for the composite anode contact device is related to the single isolated spot near the channel edge. If the edge spot is removed from the integration, no significant light emission from the composite anode contact device is observed in the bias range considered here (also shown in Figure 5).

3.2 Comparison to simulations of impact ionisation in planar Gunn diodes

The experimental results indicate that the composite anode contacts result in an overall reduction of impact ionisation in the Gunn diodes, based on the reduction of the EL from the device channel. Figures 6(a) and 6(b) show schematic diagrams of the location of impact ionisation events, obtained from Monte Carlo simulations, for both all-ohmic and composite anode contact devices. Considering first the all-ohmic device (Figure 6(a)), it can be observed that a large number of impact ionisation events take place near the anode edge. This is consistent with the picture of a Gunn domain that grows along its way towards the anode and releases its energy at the anode edge, where the high energy conduction band electrons within the domain can interact with the high density of conduction band electrons beneath the anode. As a result of this interaction, a large number of electrons in the conduction band acquire enough energy to be able to excite electrons in the valence band through impact ionisation. On the other hand, in devices featuring a composite anode contact (Figure 6(b)) the number of impact ionisation events is about five times lower than for the all-ohmic approach. In this case, when the charge density of the Gunn domain reaches the Schottky contact edge, there is a lower density of conduction band electrons than in the all-ohmic case to interact with. Thus, the total number of electrons that acquire enough energy to produce impact ionisation is lower in this case. These simulations therefore illustrate that the reduced carrier density underneath the Schottky contact is the main reason why there is less impact ionisation in the composite anode contact devices.

It is worth to note here that the high electron density inside the Gunn domain is not confined to the GaAs channel, but rather extends well outside it, as illustrated in the work by Pilgrim *et al.* [12]. This explains why Figures 6(a) and (b) show so many impact ionisation events taking place outside the GaAs channel.

It was stated in the introduction that the use of the composite anode contacts was expected to result in a reduction of the peak electric field in the planar Gunn diode. On the other hand, the results of Figure 6 suggest that it is the reduced electron density beneath the composite anode contact which is playing the major role in the reduction of impact ionisation. In order to clarify this point, the electric field distribution from Monte Carlo simulations in planar Gunn devices featuring both contacting approaches is shown in Figure 7(a) and (b). It can be seen how, when the Gunn domain exits the device, high electric fields are present near the anode contact edge in both cases, although the maximum electric field is ~15% higher in the all-ohmic case. Moreover, the changes in electric field are faster and more dramatic in the device with the ohmic anode contact (Figure 7(a)). The reason for this strong electric field changes is the depletion of the high electron density beneath the all-ohmic contact when the depleted front of the Gunn domain reaches the anode. Therefore, the reduced electron density beneath the Schottky extension of the composite anode contact has two effects that help reduce impact ionisation. First, the total number of electrons with enough energy to produce impact ionisation is reduced with respect to the all-ohmic case. Second, the reduced density of electrons beneath the Schottky extension results in a weaker electric field showing slower and less strong changes near the anode edge than in the all-ohmic case. The combination of these two mechanisms is the cause for the reduction of the impact ionisation in composite anode contact devices.

The impact ionisation events, and thus the generation of holes, take place mainly near the anode contact edge. Nevertheless, as the time it takes for the holes to reach the cathode is much shorter than their recombination lifetime, holes can populate the whole transit region, obviously with a hole density decreasing the further away from the anode contact towards the cathode, with some holes also exiting through the cathode contact. Indeed, as observed experimentally, EL is most intense at the anode edge of the channel, becoming fainter further towards the cathode contact, in agreement with this explanation.

Figure 8 shows current multiplication curves for both device structures from the Monte Carlo simulation. The current multiplication factor is defined as the ratio of the current considering impact ionisation to the current without taking it into account. In agreement with Figure 6 and the EL experiments (Figure 5), impact ionisation is decreased for the devices with composite anode contacts. These results therefore also indicate that EL is a good and valuable experimental tool for analysing carrier multiplication processes in Gunn diodes. It is evident from Figure 6 that at 5 V (i.e. the maximum bias employed in the measurements of Figures 4 and 5) impact ionisation is already present in the all-ohmic device, whereas, in the composite anode contact device, impact ionisation only becomes significant when the bias is increased to ~6 V. This is consistent with Figures 4 and 5 provided that the emission of EL near the channel edge in the composite anode contact device is not taken into account: at 5 V there is a strong emission from all-ohmic devices, whereas no light is emitted from the composite anode contact device channel. Indeed, the simulation results presented in this section support the attribution of the edge-located EL spots to some kind of border effect, like, for example, strong local variations in the electric field, that were not considered in the simulation.

3.4 Gunn diode RF operation

So far, it has been shown that devices featuring a composite anode contact show a reduced impact ionisation rate mainly due to a lower electron density beneath the Schottky extension at the anode contact edge in this type of device. This result, together with what has been previously reported on the enhancement of the breakdown voltage and the reduction of the dissipated power in composite anode devices [18], supports the composite anode contact approach as an enhanced recipe for achieving planar Gunn diodes, in terms of performance and ultimately the long term reliability potential of the devices. The performance of both the all-ohmic and the composite anode contact devices investigated here was therefore compared from the point of view of RF operation. Operation at 109 GHz with a peak power of -5 dBm (i.e. an efficiency of ~0.3%) was observed on the 1.3 μm composite anode contact devices, as shown in Figure 9. These are very promising results in terms of operation frequency, although the emitted power was rather low (~300 μW). In order to increase the output power to a useful value of ~1 mW or even higher, further development of the devices will be required, in particular with regard to the diode thermal management presently limiting the output power (see, for example, [9], where the impact of Joule heating on the *I-V* characteristics of similar devices is addressed).

On the contrary, the all-ohmic devices tested failed prematurely before it was possible to record any RF spectrum. This is a further confirmation of the usefulness of the composite anode contact approach presented in this work. Such contact design, effectively influencing energy distribution in key device areas, could also be useful for other type of devices showing impact ionisation, as stated above.

4. Conclusions

A comparison was made between GaAs-based planar Gunn diodes with both anode and cathode ohmic contacts and devices where the anode ohmic contact had an overhanging Schottky extension. It was shown that EL emission centred around the GaAs band gap is observable above a certain bias value in the saturation region of the *I-V* curves. Its origin lies in the recombination between electrons in the GaAs channel and holes generated by impact ionisation when the Gunn domain reaches the anode contact edge. The composite anode contact approach was shown to hinder the appearance of EL on the device channel indicating a much lower impact ionisation in this case. This reduction of impact ionisation was confirmed in a Monte Carlo model, and was found to be related to a lower density of electrons that can interact with the Gunn domain beneath the Schottky extension of the composite anode contact, thereby weakening the domain electric field and softening its variations near the anode edge and also reducing the total number of electrons with enough energy to produce impact ionisation. The simulated current multiplication curves were found to be in good agreement with the dependence of the EL intensity on the applied bias. As consequence of the reduced impact ionisation rate in the composite anode contact devices, an RF signal at a frequency of 109 GHz with a power of -5 dBm was observed, whereas no oscillations were observable from all-ohmic devices at identical contact spacing and operational conditions due to early device failure.

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Figures and tables

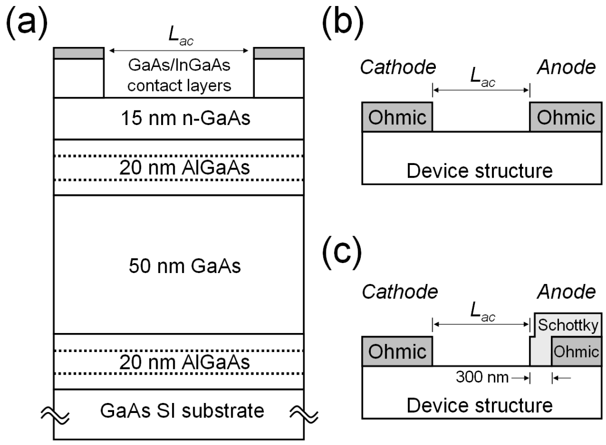


Figure 1. (a) Schematic of the planar Gunn diode device structure. Dotted lines indicate the location of the δ-doping layers; (b) schematics of the all-ohmic contacts, and (c) composite anode contact approaches.

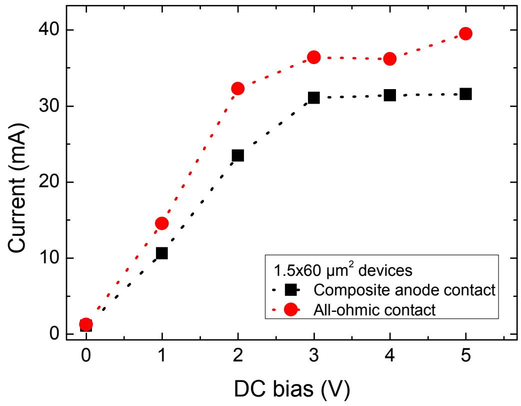


Figure 2. *I-V* characteristics of representative planar GaAs Gunn diode devices with all-ohmic and composite anode contact approaches. Anode – cathode contact spacing is 1.5 µm, with the devices being 60 µm wide.

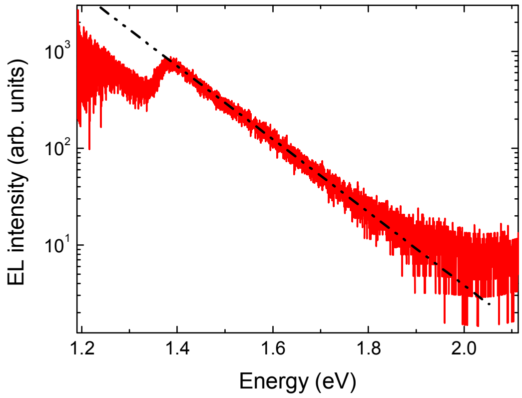


Figure 3. EL spectra from an all-ohmic device measured at 4.5 V, 42 mA. The straight line is a fit to the high energy tail of the spectra, through which an electron temperature ~1200 K is calculated. Device length is 1 µm, and device width is 60 µm.

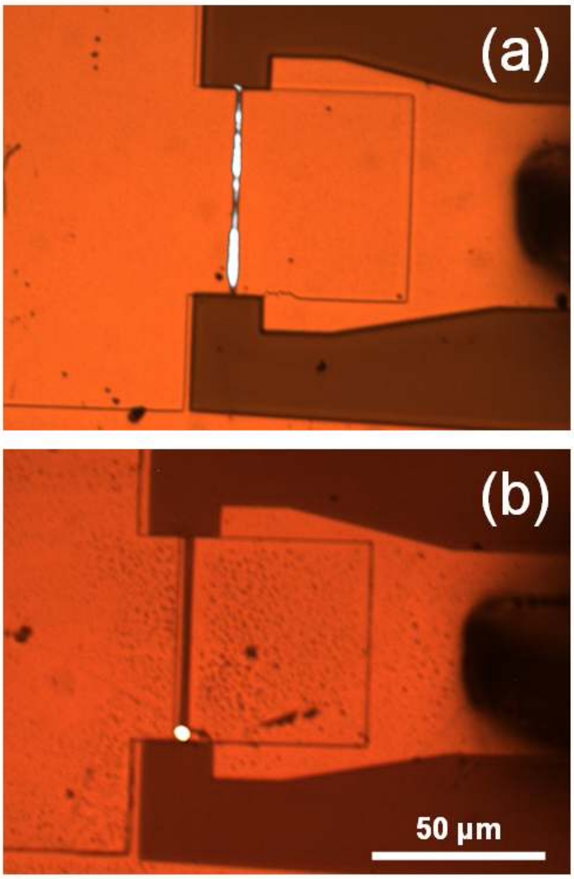


Figure 4. EL images of representative all-ohmic (a) and composite anode contact (b) planar Gunn devices taken at 5 V DC bias voltage. The EL image is overlaid on a picture of the device taken under white light illumination. The cathode contact is on the left-hand side of the pictures, whereas the anode contact is on the right-hand side. Device dimensions are 1.5 µm length and 60 µm width.

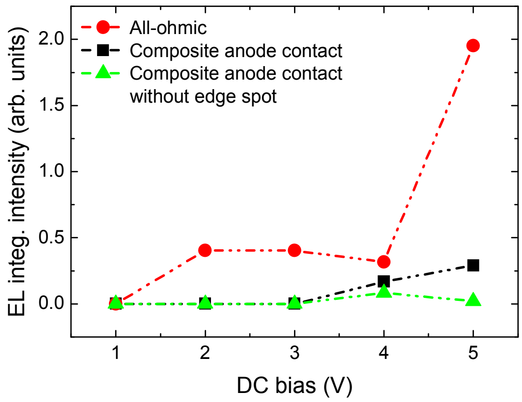


Figure 5. EL integrated intensity from the whole device channel taken from top view EL images as a function of the DC bias voltage. The integrated intensity from the composite anode contact device excluding the edge spot is also shown. Channel length is 1.5 µm, device width is 60 µm.

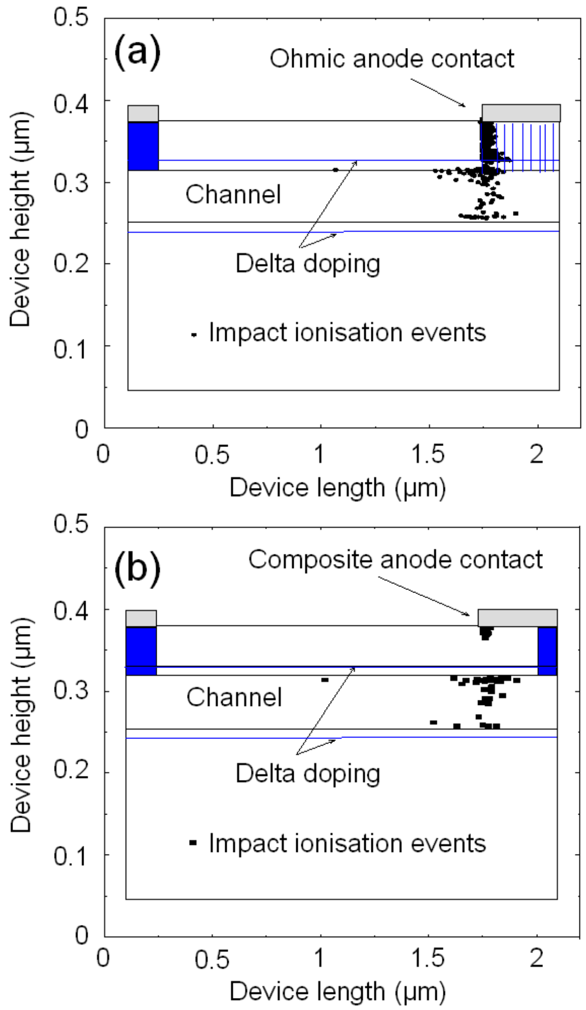
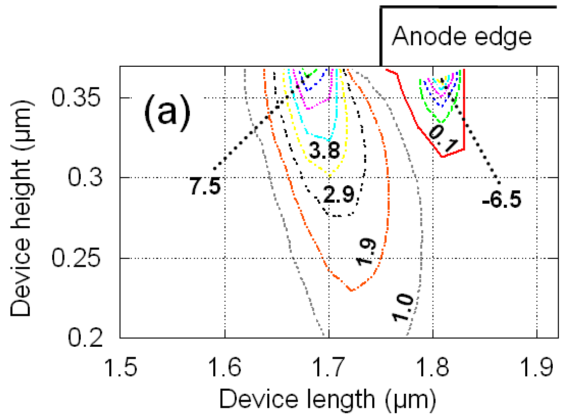


Figure 6. Schematic longitudinal section diagram of 1.5 µm-long all-ohmic (a) and composite anode contact (b) devices showing the appearance of impact ionisation events (dots) from Monte Carlo simulations, when biased at 5.5 V. Schottky extension in the composite anode contact device is 300 nm long. Blue-shaded and dashed areas beneath the contacts indicate a higher electron density.



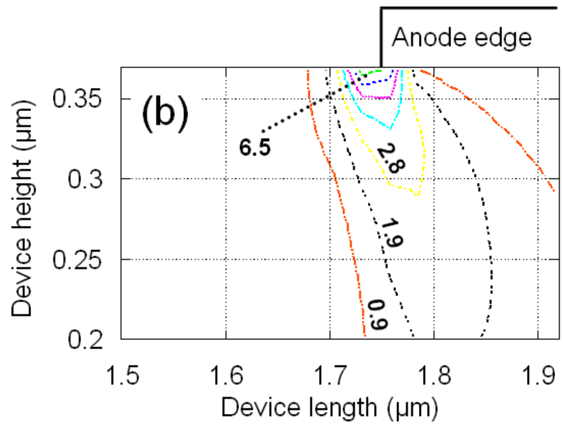


Figure 7. Electric field distribution in the vicinity of the anode contact edge when a Gunn domain exits the device. Obtained from Monte Carlo simulations for the 1.5 μm-long all-ohmic (a) and composite anode contact (b) devices, when biased at 5.5 V. Numbers indicate the value of the electric field contours in units of 10^7 V/m. Step between contours is 0.93×10^7 V/m in both figures.

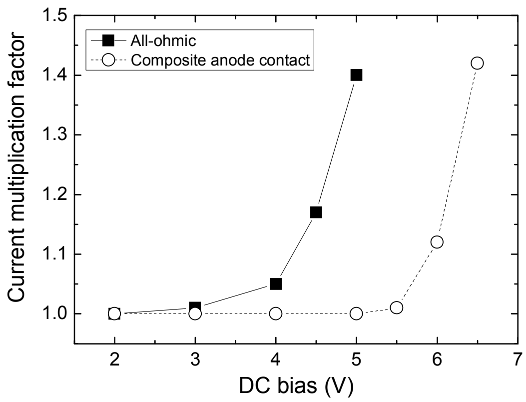


Figure 8. Current multiplication factor from Monte Carlo simulation due to impact ionisation for both 1.5 μm-long all-ohmic and composite anode contact devices.

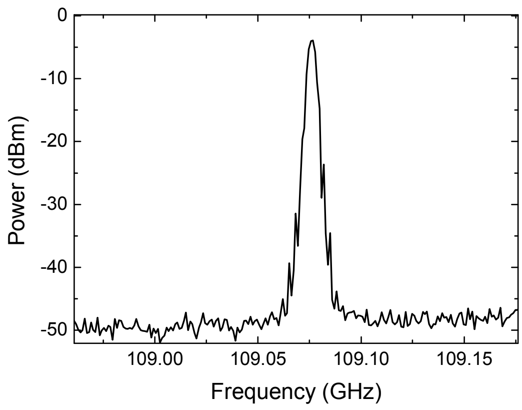


Figure 9. RF spectrum from a composite anode contact planar Gunn diode operated at 3.5 V. No RF signal was obtained from all-ohmic devices due to premature device failure.